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13. ABSTRACT (Maximum 200 words)

The Final Report documents the first fifteen months of work on an experimental investigation of the sources of combustion instability in liquid propellant rocket motors using coaxial injectors. Three possible contributions to combustion instability are being investigated: atomization characteristics, flameholding by means of a recirculation region at the base of the LOX post and gas side injector coupling. The atomization is characterized by means of a Phase Doppler Particle Analyzer (PDPA). Initial results are presented for a full size SSME preburner injector operating with water and air at atmospheric pressure. Future experiments are planned using either liquid nitrogen or liquid oxygen with either nitrogen or helium as the simulant gas at chamber pressures up to 10 MPa. In order to simulate the hydrogen temperature ramping test, a liquid nitrogen heat exchanger to cool the simulant gas has been designed and is under construction. An LDV system has been assembled to probe the region at the base of the LOX post to determine if a recirculation region exists there and if so to measure its strength.

14. SUBJECT TERMS
Combustion instability, Liquid rocket motors, Coaxial injectors, Phase Doppler Particle Analyzer

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LIQUID MOTOR COMBUSTION STABILITY USING COAXIAL INJECTORS

Final Report
for the period
10/1/91 - 12/31/92

Submitted to:

Air Force Office of Scientific Research
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WORK STATEMENT

1. Use planar laser imaging and a Phase Doppler Particle Analyzer to measure the spray size and velocity distribution and atomization zone length from coaxial injectors under steady conditions as a function of decreasing injected gas temperature. Liquid oxygen will be used for the central liquid flow and either nitrogen or helium for the outer annular gas. The possibility of using gaseous hydrogen for the final series of tests will be examined. Use planar laser imaging and possibly LDV with a transparent injector to examine the recirculation region at the base of the injector. The following parameters will be investigated:

   a) Chamber pressures up to 1500 psia.

   b) Injector design in terms of flow area ratio, LOX post tip land width and liquid flow recess distance.

2. Use the measured spray size and velocity distributions as input to ONERA and Penn State numerical codes to examine the effects of atomization on predicted motor stability and to establish an experimental database to provide guidance towards the development of an atomization model. Compare results to hydrogen temperature ramping test results where available (NASA Lewis, Rocketdyne).

INTRODUCTION

Although stable operating regimes for cryogenic coaxial injectors have been experimentally determined, there is no knowledge of the spray characteristics (i.e. droplet size and velocity distribution) corresponding to stable operation or the physical processes which produce the atomization patterns that result in stable or unstable operation. The current engineering method for determining the stable operating regime of a cryogenic coaxial injector is the "hydrogen temperature ramping" method. One or more injectors are placed in a combustion chamber and hot fired while the temperature of the gaseous hydrogen being injected is slowly reduced until a spontaneous instability occurs. The physical significance of the hydrogen temperature ramping technique comes from the atomization process occurring in coaxial injectors where the high velocity outer gaseous hydrogen flow strips droplets from the lower velocity inner liquid oxygen flow. Experiments at ONERA using water as the liquid oxygen simulant have shown that a higher relative velocity between the two flows, one gaseous and the other liquid, results in smaller droplets and complete atomization closer to the injector exit[1]. Lowering the gaseous hydrogen temperature increases its density, thus lowering its injection velocity relative to the liquid in order to maintain the same mass flow and therefore the same fuel-to-oxygen ratio. Wanhainen et al have shown that it is not the hydrogen temperature itself causing the transition to instability but the ratio of the gas to liquid injection velocities[2]. From this one might infer that the instability arises because of an increase in the liquid oxygen drop sizes along with an extension in the length of the atomization zone. A primary purpose of the proposed experiments is to identify what effect the velocity ratio has on atomization and pressure drop across the injector to provide a better understanding of this common stability rating technique. A more practical disadvantage to the hydrogen temperature ramping technique is that the occurrence of the spontaneous instability can lead to the destruction of the test motor within seconds.

Another proposed explanation for the emergence of unstable operation in the hydrogen temperature ramping test is that a recirculation region acting as a flameholder exists downstream of the LOX post tip. Below a minimum relative velocity between the liquid oxygen and gaseous hydrogen, the recirculation region becomes too weak to act as a flameholder and the combustion zone moves away from the injector face to a location where it can interact more strongly with the chamber acoustic modes. Liang and Schumann have examined this idea with an experimental and computational investigation of gaseous oxygen and hydrogen coaxial injectors[3]. They examined several injectors designed to produce recirculation regions of different sizes but found that all injectors tested showed the combustion region anchored to the base of the injector. Finally, there is no knowledge of the effect of operating above the critical temperature and pressure (supercritical) on the atomization characteristics themselves or on the combustion stability of the motor.

RESULTS

The first nine months of the grant period were spent designing a liquid nitrogen cooled heat exchanger to lower the temperature of the injected gas, either hydrogen or helium, from ambient down to 80K. The design has been completed and construction has begun. The heat exchanger will be used for the final series of experiments to simulate the hydrogen temperature ramping test and examine the effect of temperature induced gas velocity changes on the resultant atomization and its subsequent effect on motor instability.

An injector with the same dimensions as the SSME preburner injector has been constructed and tested with water and air at atmospheric conditions (Fig. 1). The SSME preburner injector was selected because the test facility is capable of providing the required gas and liquid mass flow rates for a full size injector and as large an injector as possible was desired to provide the possibility of optical access. The initial tests of the injector used air and water injecting into atmospheric ambient pressure. Figures 2a and b show the injector operating with water and air at two different velocity ratios. It is readily apparent that much better atomization is obtained by a higher ratio of velocities between the fluid and the gas.

PDPA measurements were made of the droplet size and velocity as a function of axial and radial position for two values of the velocity ratio. Figures 3a and b show the measured droplet Sauter mean diameters and velocities as a function of axial and radial position. It can be seen that the radial profiles for both the droplet size and velocity flatten as one moves down the axis away from the injector face. The drop size on the axis increases while the drop velocity decreases as one moves down axis. The main purpose for this limited series of tests was to confirm the operation of the PDPA system as well as the injector. As can be seen from Figures 3a and b, there was some asymmetry in the spray, probably due to a slight misalignment of the central LOX post.

In order to determine if a recirculation region exists at the base of the LOX post, a miniature diode laser LDV system has been assembled. It will be used to probe the region at the base of the LOX post to determine if and under what circumstances a recirculation region exists. The LDV will use liquid droplets produced by the atomization process as the seeding particles. If a recirculation region is found to exist, an attempt will be made with the LDV to measure its strength.

In the course of an extensive literature review conducted during the course of this year, some previous experimental evidence was found that indicated that the spontaneous stability condition for a hydrogen/oxygen rocket was determined by the hydrogen pressure drop through the injector[4,5]. Below a critical minimum value for the pressure drop, chamber oscillations evidently can couple to the propellant feed system, causing a combustion instability in the chamber. However, the value of this critical pressure drop was a function of the injector and chamber design.

Measurements of the injector pressure drop as a function of the relative gas/liquid flow velocity and injector geometry are planned. The results of these measurements will be used as input to a stability model of the propellant feed system to determine the magnitude of the influence of the injector pressure drop on the combustion stability of the entire motor.

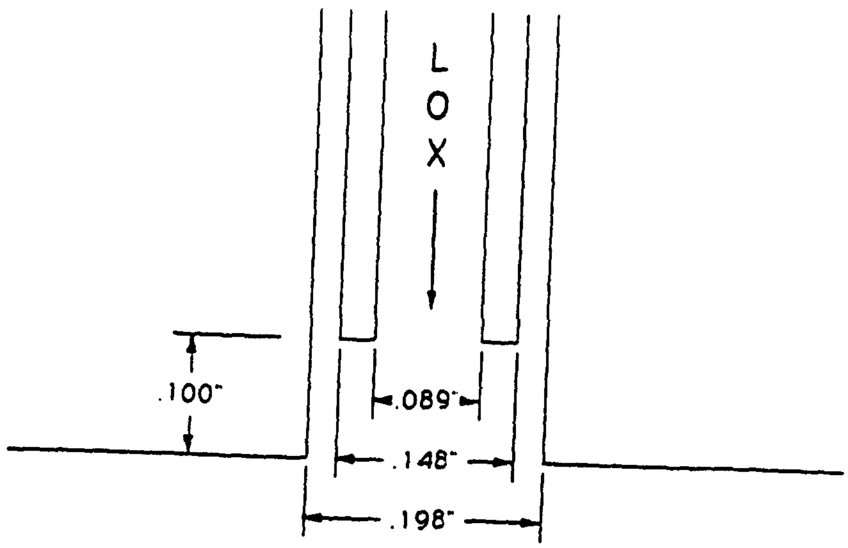

Fig. 1 Dimensions of SSME preburner injector.

Fig. 2a Injector operating at atmospheric conditions with air and water with gas/liquid velocity and momentum ratios of 66 and 0.08 respectively.

Fig. 2b Injector operating at atmospheric conditions with air and water with gas/liquid velocity and momentum ratios of 190 and 0.26 respectively.

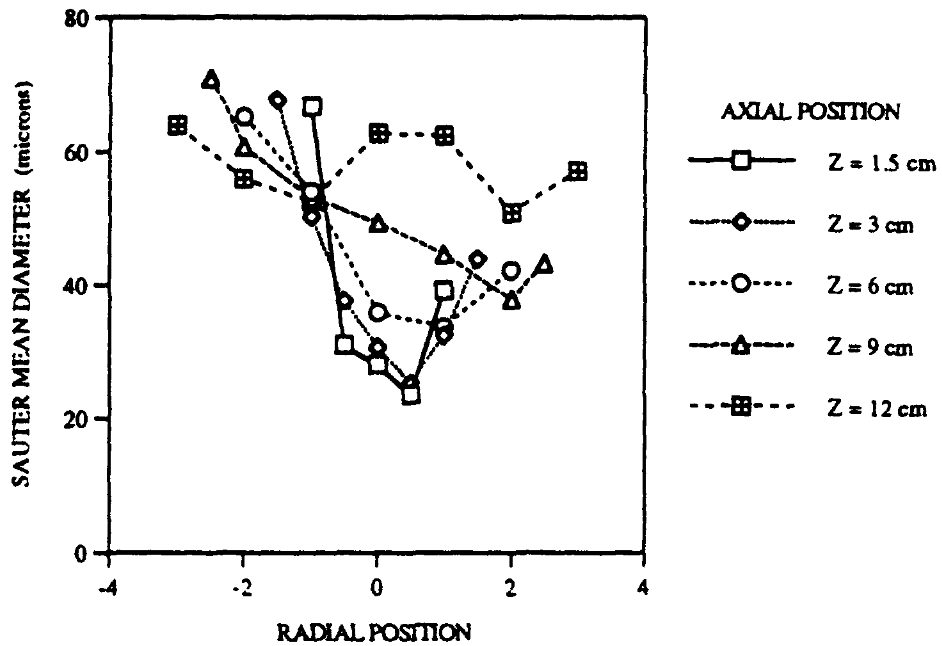

Fig. 3a Droplet Sauter mean diameter for an atmospheric water/air shear coaxial injector spray as a function of radial and axial position.

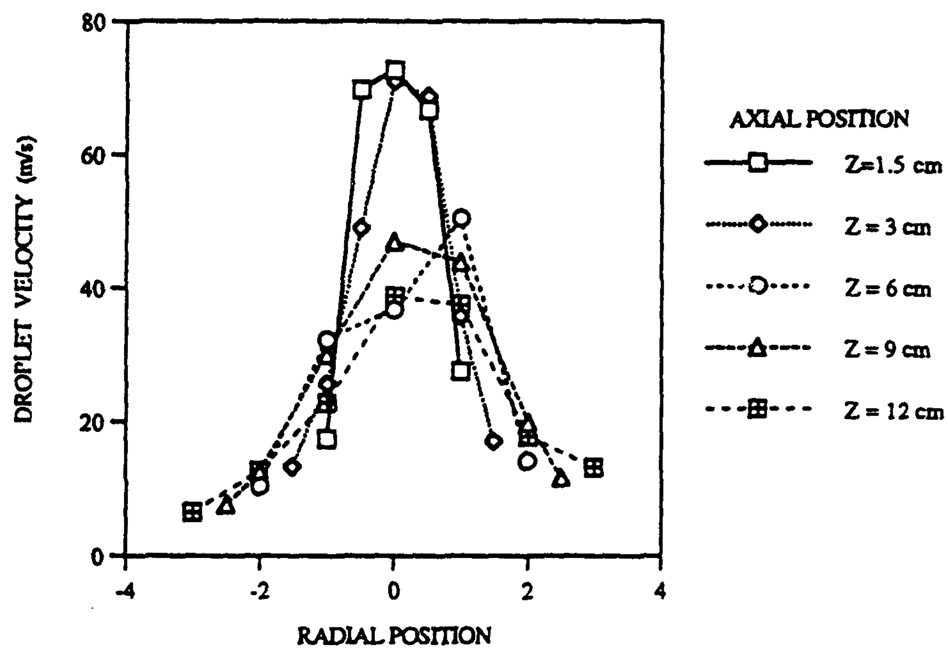

Fig. 3b Droplet velocities for a water/air shear coaxial injector spray as a function of radial and axial position.

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CUMULATIVE CHRONOLOGICAL LIST OF WRITTEN PUBLICATIONS

"Shear Coaxial Injector Spray Characterization," Glogowski, M., Milicic, M. and Micci, M. To be presented at the 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 28-30, 1993, Monterey, CA. To be submitted to the Journal of Propulsion and Power, July 1993.

LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Professional Staff

Michael M. Micci, Associate Professor, Aerospace Engineering

Graduate Students

Michael Glogowski, August 1991 - present
Marty Milicic, August 1991 - present
Teresa Kaltz, August 1992 - present

INTERACTIONS

Papers Presented

"Combustion Instability with Coaxial Injectors," Micci, M. M. Presented at the AFOSR Contractor's Meeting on Propulsion, June 15-19, 1992, San Diego, CA.

"Shear Coaxial Injector Instability Mechanisms," Micci, M.M., Glogowski, M. and Milicic, M. Presented at the Fourth Annual Symposium of the NASA/Penn State Propulsion Engineering Research Center, Sept. 9-10, 1992, Marshall Space Flight Center, Huntsville, AL.

Visits

One day trip to Hobart - Tafa, Inc., Concord, NH, May 1, 1992, to discuss the use of a shear coaxial injector in the flame sprayer which they manufacture.